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**Report on the 29th International Rarefied Gas Dynamics Symposium  
held at Xi'an China, July 13–18, 2014**

Hans G. Hornung

## **1 Introduction**

This document aims to provide information to the United States Air Force about the 29th International Symposium on Rarefied Gas Dynamics (RGD29) held in Xi'an, China, July 13–18, 2014. The RGD Symposia take place every two years. They are a forum at which scientists and engineers report new developments in the field. The scope of the fields of interest to the Symposia can best be gleaned from the list of topics from which contributions were solicited by the RGD29:

Boltzmann and Related Equations  
Clusters and Aerosols  
DSMC and Related Simulations  
Experimental Procedures in RGD  
Gas-Surface Interactions  
Granular Fluids  
Hybrid Methods  
Jet and Plumes  
Kinetic and Transport Theory  
Micro- and Nano-scale Flows and Devices  
Molecular Beam and Collisions  
Molecular Dynamics Simulations  
Numerical Solutions of Kinetic Equations  
Particle Methods for Flow Simulations  
Plasma Flows and Processing  
Radiation and Plasma Flows  
RGD in Astrophysics  
Reaction and Relaxation Processes  
Space Vehicles Aerodynamics  
Turbulence  
Vacuum Gas Dynamics

The most important characteristic of all these topics is that they contain problems in which

the average distance travelled by a gas molecule between collisions, called the mean free path  $\lambda$ , is of similar order or larger than a characteristic geometrical length defining the problem,  $L$ . The ratio of these two lengths is called the Knudsen number  $K$ , and the above condition may be written as

$$K \equiv \frac{\lambda}{L} \geq 1.$$

This is the flow regime of interest to the RGD's. For the purpose of this introduction it is worth highlighting two important features: Because the response of a gas to changes imposed by the flow occurs via collisions between the gas molecules, the above condition means that the gas may not be able to respond fast enough. This often leads to non-equilibrium situations. Another important difference relative to continuum flows (in which  $K \ll 1$ ), is that the boundary conditions at a solid wall become much more complex.

After a section describing the organization of the symposium, a fairly detailed discussion of the plenary presentations, as well as of individual talks attended by the author will be given. Since the conference was organized in three parallel sessions, the latter necessarily has to be a selection. The report concludes with some general comments.

The meeting was attended by 217 participants from 22 countries. 71 of the participants were students, see details in Appendix.

## 2 Organization of the Symposium

The conference was chaired by Professor Jing Fan, Director of the Institute of Mechanics of the Chinese Academy of Sciences at Beijing, a prominent leader in the field. The general planning of the RGD's is organized by an International Advisory Committee:

T. Abe (Japan)	K. Aoki (Japan)	D. Bruno (Italy)
R. Campargue (France)	C. Day (Germany)	J. Fan (China)
A. Frezzotti (Italy)	M.A. Gallis (USA)	R. Gatignol (France)
M.-A. Gaveau (France)	A. Ketsdever (USA)	E. Knuth (USA)
G.M. Kremer (Brazil)	E.V. Kustova (Russia)	D. Levin (USA)
E.P. Muntz (USA)	T. Niimi (Japan)	A.K. Rebrov (Russia)
A. Santos (Spain)	B. Shizgal (Canada)	H. Struchtrup (Canada)
I. Wysong (USA)		

Members typically stay in this committee for a number of years.

Professor Jing Fan was assisted by the Local Organizing Committee, consisting of ten Chinese scientists, for the detailed planning and organization of the conference.

The symposium organizers reached the community with a very well designed web site that must have had quite a team behind it. Authors found the response of this team to questions very prompt, and the mechanism of obtaining visas worked very well. The instructions for authors including those for preparation of papers for the proceedings were easy to follow.

The symposium organizers also provided a special shuttle service from the airport to the Hilton Hotel where the symposium was being held. Throughout the conference the logistics and timing proceeded very smoothly. The layout of the coffee-break venues were nicely suited to interactions between the participants.

The printed program had some very useful features: A page showing the whole week with a color scheme distinguishing session types. A program summary with a page per day, showing all parallel sessions with one author's name only per presentation. This was followed by a detailed program in which all authors' names and the presentation title were given and the parallel sessions were shown with one page per period between breaks. This layout together with the book of abstracts made it very convenient to plan attendance. The participants were provided with a CD of the book of abstracts. I later found that it is difficult to find particular abstracts in this, because there is no index in in the CD.

The opening session with welcome by the chair and a little history of Xi'an was followed by a very charming shadowplay show of a story involving a crane and a tortoise. Classy and sophisticated.

The Wednesday afternoon excursion to the historically interesting Small Wild Goose Pagoda and to the City Wall with many buses worked well. The day was completed by a very spectacular operatic style show on a large stage accompanying the banquet. It told the story of a king who had his people recreate a dream that he had had.

The symposium ended with a charming farewell party at which photographs taken during the week were shown.

### **3 The plenary and invited lectures**

In this section I describe the presentations I attended. These descriptions are subjective (hence written in the first person) and when I did not understand everything, they may be

incomplete or even incorrect.

### 3.1 Plenary lectures

The RGD Symposia feature three named plenary lectures honoring prominent scientists in the field: Harold Grad, a prominent American applied mathematician; Lloyd Thomas, a gifted American molecular beam experimenter; and Graeme Bird, an Australian who pioneered the numerical method he called Direct Simulation Monte Carlo (DSMC) technique.

The Grad lecture was presented by Mario Pulvirenti, a mathematical physicist at the University of Rome. His title was "Quantitative analysis of the correlations in the Boltzmann–Grad limit for hard spheres". The theory presented sets out to derive the Boltzmann equation from a rigorous application of Newtonian mechanics to an  $N$ -body system. It is claimed that this may be done in a certain very rarefied limiting case. It seemed to me that this has a conceptual problem, because Newtonian mechanics is deterministic while the Boltzmann equation is based on a statistical description of a large number of particles. Pulvirenti, however, speaks of providing "quantitative estimates of the propagation of chaos". Here we already have one of the cases in which I have to admit some lack of understanding.

The Thomas lecture was given by Aleksey Rebrov, prominent in the Siberian Branch of the Russian Academy of Science, a well-respected experimenter in RGD. His topic was "Nanostructure synthesis from high velocity gas mixture flows". He described experimental techniques that he applies mainly to anti-bacterial film deposition and production of diamond. In both, a heated vapor expands through a nozzle to a high velocity. This flow impinges on a solid surface in a vacuum chamber at typically 500 m/s. It is advantageous to admix a heavy gas for more rapid deposition. For anti-bacterial coating two jets are combined, one of silver and one of Teflon. For diamond deposition the Spitsin method uses a seed crystal placed on the surface, and hydrogen and methane jets expanded from 2300 °C impinge on it. A more successful method is the Kurihara plasma jet with which growth rates of up to 80  $\mu\text{m/h}$  have been achieved. Subtle experimental details such as sensitivity to the distance from the jet to the substrate and applying a voltage difference were discovered. Matsumoto achieved growth rates up to 900  $\mu\text{m/h}$ . Sophisticated diagnostic techniques used in Rebrov's laboratory include emission spectroscopy, Laser Induced Fluorescence (LIF), Cavity Ring-Down Spectroscopy (CRDS) for temperature and density measurement, and Resonance-Enhanced Multiphoton Ionization (REMPI). The lecture described important progress in techniques that may improve industrial diamond production. Many empirically found rules and guidelines are buried in this research.

The Bird lecture was given by Michael Gallis of the Sandia National Laboratory in Albuquerque, New Mexico. His title was "Direct simulation Monte Carlo: The quest for speed". After a historical introduction he showed how the early development of DSMC was dogged by computational power limitations. The method was also considered slow and not mathematically well founded. Modern DSMC codes have dispelled such opinions. Gallis showed with simple flow examples that DSMC simulations give excellent agreement with the Boltzmann equations and with experiment, and that they can describe molecular processes without requiring the models needed in other methods for transport and non-equilibrium phenomena. He pointed out that the stochastic noise introduced by DSMC is related to the fluctuations in actual gases. The Navier–Stokes approach is deterministic and has no stochastic component. He showed three images of the density interface in a Richtmyer–Meshkov instability. One experimental, one simulated by Navier–Stokes and one simulated by DSMC. The slight irregularity in the experiment is similar to that in the DSMC simulation, but is absent in the NS simulation. (Of course, such an irregularity could be generated in an NS simulation by introducing some stochastic noise). Gallis went on to discuss improvements in DSMC such as virtual subcells versus transient adaptive subcells and stochastic vs. deterministic determination of nearest neighbors. He concluded with the important point that DSMC is naturally parallelizable unlike solvers of partial differential equations. It led Gallis to conclude that with expected increases of computational power and because of its other good features it may become the preferred method even for continuum flows. He makes his DSMC code publicly available on <http://sparta.sandia.gov>

### **3.2 Invited lectures**

There were ten invited lectures in the program. These were not plenary, each was part of a session in parallel to two other sessions. For this reason I attended only three of these. I found it interesting that the organizers chose some of these invited talks from fields somewhat outside RGD, a healthy look over the fence.

In the session on Granular Fluids, Stefan Luding from the University of Twente in the Netherlands presented "From particles to continuum theory - from slow to rapid flow", in which he described results obtained from particle dynamics simulations of particulate systems over a considerable range of the parameter space. Interesting phenomena include transitions from homogeneous behavior to clustering and non-Newtonian phenomena. Various regimes of flow were delineated. My impression was that Luding's work would be a good starting point for someone interested in getting a grip on this field.

In one of the sessions on Molecular Beams and Collisions, Paul Dunk of Florida State University together with eight international co-authors presented "Recent advances in Fullerene Science", a fairly comprehensive account of sophisticated experimental work to study the many different geometries achievable in bucky balls and fullerenes generally. The experiments involve the use of a 9.4 Tesla superconducting magnet enabling high resolution Fourier Transform ion cyclotron resonance mass spectrometry. This represents a significant advance in experimentation in this field. At the end of the talk he gave a discussion of fullerenes in space. In the Murchison meteorite there is evidence of the production of  $^{22}\text{Ne}$  from  $^{22}\text{Na}$ , which is argued to have been possible only in supernovae before the existence of the solar system.

Also in the session on Molecular Beams John Maier of the University of Basel, Switzerland presented "Electronic spectra of organic molecules of relevance to combustion, atmospheres and interstellar space". He was introduced by Prof. Campargue from France, who pointed out that there used to be up to 50 presentations on molecular beams in RGD Symposia in the 1980's whereas now there were only a very few. The talk described very sophisticated experiments that were able for the first time to determine the reactive intermediate species in the organic reactions encountered in the fields listed in the title. The experiments employ REMPI, CRDS and degenerate four-wave mixing. Astronomers have been able to identify many organic molecules in dark clouds by absorption spectroscopy. The lab experiments are compared with results from the Keck Telescope. He described some really interesting sleuthing in order to find species that have spectral lines with large oscillator strength. One of the problems of the supersonic expansion used for the molecular beam is that the vibrational excitation of the molecules freezes, a feature that is absent in the interstellar gas. To let this excitation relax in the lab, they keep the gas in an ion trap at 5 K for long enough to make it equilibrate.

One invited talk that I did not attend, but had heard in the International Symposium on Shock Waves in Madison, Wisconsin in July 2013, was "Development of the advanced high-enthalpy shock tunnel for hypersonic vehicles" by Jiang and Yu of the Chinese Academy of Sciences in Beijing. This is worth mentioning, because it is the largest facility of its type, and in fact is unique in that it uses a detonation driver. It is able to produce flows at up to 4 km/s in a 2.5 m diameter test section. The total length of the facility is 265 m. This is an example of the rapid strides that Chinese technology is making.



## 4 Discussion of selected presentations

Most of the regular oral presentations were allocated 15 minute time slots in three parallel sessions. Time was kept fairly punctually and the rooms were close enough together to enable switching attendance between sessions. In this section I will report on the regular oral presentations in the order in which I attended them.

Kazuo Aoki with three co-authors presented "Numerical study of the Taylor-vortex flow of a slightly rarefied gas." This classical problem has been studied extensively both in the continuum and rarefied flow regimes, but, because of the computational expense not much attention has been given to the intermediate Knudsen number range. This is where they tackle the problem comparing results from the compressible Navier–Stokes equations with slip with those using DSMC. Very good agreement is found. This is a fairly comprehensive piece of work in which interesting scaling has been found that collapses the data in various regions.

Satoshi Taguchi presented "Drag of a sphere in slow uniform flow of a rarefied gas". He considers the case of  $K = O(1)$  and solves the near field with the non-linear Boltzmann equation for small Mach number. In the far field he uses an analytical solution in an expansion for small Mach number and matches to the near-field numerical solution. The results yield an expression that gives the first non-linear term for the drag coefficient.

Vladimir Istomin and co-author presented "Effect of electronic excitation on high-temperature flows behind strong shock waves". They compute one-dimensional non-equilibrium continuum flow of nitrogen through a normal shock wave. They consider the five species  $N_2$ ,  $N_2^+$ ,  $N$ ,  $N^+$  and  $e^-$ , with rotational and vibrational excitation in the molecular species, many electronic excitation levels. In such a flow there usually occurs a phenomenon called the electron cascade, a sudden increase of the degree of ionization that happens a short distance downstream of the shock wave because the ionization rate increases very rapidly as soon as electrons appear. This – puzzlingly – was not evident in their results. It was not possible to see the details in the list of reactions that was shown to sort out why.

Jacob Graul and Taylor Lilly were the authors of "Coherent Rayleigh–Brillouin scattering as a flow diagnostic technique". The presenter was Lilly. A novel four-wave mixing technique employing a Fabry–Perot interferometer was shown to yield point measurements of velocity, temperature and pressure, as well as bulk viscosity in a gas.

Andrew Ketsdever with three co-authors presented "Determination of thermophoretic force on a particle in transitional flow". A particle in a gas in which there exists a temperature gradient experiences a force in a direction opposite to that of the temperature gradient.

This thermophoretic force results from molecules interacting with the particle on the hot side imparting more momentum to it than on the cold side. Thermophoresis has many important technological applications. The work described is an experimental investigation in which two  $0.6 \text{ m}^2$  plates, one of which is heated, are spaced at 0.4 m. Between the plates a 5 cm diameter copper sphere is supported by a nano–Newton thrust balance measuring the force. The temperature gradient is of the order of 20 K/m, but can be varied by changing the plate spacing. Over a certain range of temperature gradient the force is found to be proportional to the gradient and in reasonable agreement with a theoretical formula. An experimental difficulty is that the temperature gradient is not uniform between the plates. An interesting result is that the force changes sign at a Knudsen number of 0.03.

Andrew Ketsdever with four co–authors presented "Thermophoretic forces on a plate with holes in transitional flow". This investigation uses the same experimental setup as that in the previous talk. The test article this time is a plate with differently shaped and differently sized holes. It is known that the force is affected by the edges of the test article. The rate of change of the force with temperature gradient is found to increase rapidly as the perimeter ratio (perimeter/area) is increased, up to a point after which it stays constant. The flow pattern at an edge is also studied numerically using DSMC and Bathnagar–Gross–Krook approximation (BGK).

Koellermeier and Torrilhon, mathematicians from Aachen presented "Hyperbolic moment equations using quadrature–based projection methods". A problem with some methods of solving the Boltzmann equation is that they sometimes do not preserve global hyperbolicity. This can cause numerical methods to give unphysical results. The authors present a method that uses Hermite basis functions together with Gauss–Hermite quadrature to ensure hyperbolicity. They extend a previous one–dimensional method to more dimensions and compare their technique with others.

Aristov and Ilyin presented "Processes of aggression described by kinetic methods". The authors model the invasions of Poland, France and the Soviet Union by Nazi Germany with a wave–like kinetic equation like the case of one gas penetrating into another. In the spread of the plague during the Middle Ages, the characteristic speed was 200 miles/year. In the 20th century invasions it was 300 km/week. By using reasonable assumptions about density and gunfire distance they arrive at a mean free path of 1 km and obtain a wave speed of 350 km/week with their model, in reasonable agreement with the invasion of France. An interesting, different application of methods of RGD.

Manuel Vargas with four co–authors presented "Separation effects in unsteady binary gas mixture expansion into vacuum". Quasi–steady computations of flow from a small high–pressure reservoir through a short tube into a large vacuum vessel with a hybrid scheme are

described. Mixtures of monatomic gases (He/Ne, He/Ar, He/Kr) as well as single gases are used. The results are compared with experiments from PTB, Berlin. The mass separation causes the mass conductance to depend on the species. The comparison indicates that the experimental rate of pressure drop is larger than the computed value.

Hossein Gorji with two co-authors presented "Hybrid Fokker-Planck-DSMC method for rarefied gas flow simulations in the whole Knudsen number range". As we have seen in Gallis' plenary talk, using DSMC at small Knudsen numbers is computationally very expensive. For this reason, hybrid methods are often employed, in which regions of a flow field where the local Knudsen number is low are computed with continuum CFD techniques and DSMC is used only in low density regions. A problem with this approach is that the discretization methods for the two types of computation are different, so that elaborate schemes have to be employed at the interfaces. The authors of this presentation avoid this by using the Fokker-Planck approximation in the continuum regions. (Both methods use the same discretization). They demonstrate the fidelity of their approach with several test cases of flow fields in which the Knudsen number varies from  $10^{-5}$  to  $10^5$ . A speed-up of almost two orders of magnitude is observed over pure DSMC computations without any loss of accuracy. This is an important advance in numerical investigations.

Ishida, Tezuka and Abe were the authors of "Influence of gas/surface interaction on shock wave propagation through a tube". Abe was the presenter. A double-diaphragm free-piston driven shock tube is used to produce shock waves at speeds of 11-14 km/s in air at Knudsen numbers from 0.005 to 1.2 in a square shock tube. The Knudsen number was varied by changing the initial shock tube pressure at constant driver conditions. At small Knudsen numbers the attenuation of the shock speed was caused by the boundary layer generated by the shock at the tube walls. At larger Knudsen numbers the attenuation is stronger and is thought to be caused by gas/surface interaction that sends lower speed particles from the walls deep into the flow.

Hossein Gorji and Patrick Jenny of ETH presented "A demixing device based on selective excitation of polyatomic molecules". In the collisionless regime, molecules with rotational excitation increased by laser excitation come off the wall with higher translational temperature which can be used for demixing. To study this, they use DSMC with a Cercigniani-Lampis-Lord wall condition to which they have added a new diffusive kernel. They show that this addition causes a large discrepancy between computations and experiment to disappear. The device has the potential of demixing species even if their molecular weights and sizes are the same.

Struchtrup and Mohammadzadeh presented "Applications of generalized Maxwell boundary conditions". They add extra terms to a Cercigniani-Lampis-Lord model in order to

add flexibility to the wall condition. This adds four adjustable constants that permit the model to be calibrated against experiment. For example one of the terms permits the wall temperature to vary along streamwise distance which gives a tangential force.

Brull, Charrier and Mieussens presented "Boundary conditions for the Boltzmann equation for rough walls". They consider a particular regular structure of the wall and study the interaction of particles of the gas using molecular dynamics and Lennard-Jones potentials. They compute probabilities of the re-emission angle for given incoming angles. Their general conclusion is that the roughness of the wall can have a significant influence.

Kosuge presented "Effect of a boundary condition on the cylindrical Couette flow of a rarefied gas". The flow between two coaxial cylinders, the inner one rotating is studied using the BGK model equation. The normal and tangential momentum accommodation coefficients at the walls ( $\alpha$  and  $\beta$  respectively) are assumed to be different. The effect of their ratio is investigated. It is found that when  $\beta/\alpha$  is decreased to less than about 0.2, the tangential velocity gradient becomes positive, i. e., it is lower at the inner cylinder than at the outer one.

Kon, Kobayashi and Watanabe presented "Numerical analysis of kinetic boundary conditions at net evaporation/condensation interfaces in various liquid temperatures based on mean-field kinetic theory". Phase-change boundary conditions present a very tough problem. I was not able to understand this work. They used molecular dynamics to establish parameters in what they called kinetic boundary conditions.

Next I attended the session on Jets and Plumes. This was headed off by a talk from Elden Knuth, who was the oldest participant. The first talk he has ever presented at an RGD Symposium was exactly 50 years before. He has attended all but two of the RGD Symposia. Another venerable personality among the participants was Graeme Bird, who spent a lot of time in discussions with other participants. Bird has taken part at all but three RGD Symposia.

Knuth with two co-authors presented "On the roles of the binodal line, adjacent surfaces and the spinodal line in free-jet expansions from the supercritical state". In a number of experiments, time-of-flight mass spectra of such expansion show more than one peak. Knuth speculates that if the gas crosses the binodal line upstream of the sonic throat the fluid in this metastable state interacts with the adjacent surface, intermittently causing flashing. The apparent multiple peaks in the mass spectra are presumed to be present because the signal is a result of superposed data from time samples obtained by chopping.

Woronowicz with 14 co-authors presented "Analytical and experimental studies of leak

location and environment characterization for the international space station". The first author was Kelvin Garcia of NASA Goddard, who was not able to obtain authorization for travel to China. The aim of this work is to develop a robotic leak locator for the International Space Station (ISS). The instrument will use an external residual gas analyzer for partial pressure measurements. A particular target gas is ammonia from the thermal control system. Experiments on leak simulation indicate that the instrument can be made sufficiently sensitive to detect leaks of 1 lb/year.

Grabe with four co-authors presented "Numerical investigation of two interacting thruster plumes and comparison to experiment". Experimental measurements obtained in the DLR high-vacuum plume test facility STG at Göttingen, which is capable of producing space-like vacuum conditions, are compared with computations using three-dimensional DSMC in the transitional and rarefied regions of the flow and a Navier-Stokes solver in the continuum regions. The measurements were made with a Paterson probe and are difficult to interpret. A procedure is established that uses the computed flow field to reconstruct the probe signal that yields good comparison.

Liang and two co-authors presented "DSMC numerical simulation of lateral jet interaction with rarefied atmosphere". This is a state-of-the-art computational study of the title flow using hybrid DSMC.

Tang and two co-authors presented "Analysis of the effect of the plume protect cover assembled to a 60 N thruster using coupled NS/DSMC method". To prevent plume impingement on sensitive parts of a spacecraft it is proposed to place a conical cover in the region where gas expands all the way round the nozzle exit in the vacuum of space. This geometry is investigated using hybrid NS/DSMC with two different switching criteria. It is found that the cover reduces the mass flux in the backflow region significantly.

Soorkia and five co-authors presented "UV photofragmentation spectroscopy of gas phase biological molecular ions in a cold ion trap". They describe very sophisticated experiments in which the molecules are ionized and trapped in a 10 K cryogenic ion trap. This is necessary because at higher temperature the mass spectrum is so congested that one can not resolve peaks in the spectra from time-of-flight mass spectrometry. Detailed chemical mechanisms and rates are studied using the method.

Korobeishchikov and two co-authors presented "Experimental and numerical study of high-intensity argon cluster beams". Cluster ion beams have distinct advantages over ion beams, e. g., in materials processing and deposition of thin films. The formation of cluster beams is studied experimentally by varying the parameters in an expansion to supersonic flow.

Liu and two co-authors presented "Effect of growth temperature on composition control of YBCO precursor films fabricated by vapor deposition". High-temperature superconducting materials involve deposition as thin films on substrates. Although I did not understand much of this talk, the authors have clearly made significant advances in the technology of such film deposition. An important result of their study is that the substrate temperature, which needs to be high for good diffusion, affects the composition in simultaneous deposition of different materials.

Shu, Wang, Liu and Fang from the same group presented "Quantitative analysis of oxygen content in copper oxide films using ultra microbalance". By measuring vapor-deposited copper oxide films on quartz substrates with X-ray diffraction, scanning electron microscopy and with a microbalance, they demonstrate that the latter is a further useful method for quantitative measurement of oxygen content to high accuracy.

Next I attended two sessions that were dedicated to the memory of Mikhail Ivanov, a prolific contributor to previous RGD Symposia, who passed away last year. The first presentation was by Sun, Liang, Cai and Fan (the chair of the Symposium) and was entitled "A "smile" memory in China's RGD community: Mikhail Ivanov's academic links". Sun presented photographs and heart-warming stories of encounters between Chinese scientists on various visits. He also showed how the two codes SMILE and RUSAT, developed by Ivanov's group have helped the Chinese community.

Kashkovsky, with co-authors Bondar and Gimelshein presented "Computational tools for high-altitude aerodynamics: In memory of Mikhail Ivanov". The group around Ivanov, over a number of years, have built up tools that make three-dimensional DSMC accessible to engineering use on bodies with complex geometry. This has become a very valuable resource for satellite aerodynamics and flow over all kinds of objects at high altitude. The tools were described in some detail.

My presentation "Mach reflection in steady flow: I. Mikhail Ivanov's contributions, II. Caltech stability experiments". In the first part I showed the important discovery by Ivanov that hysteresis does indeed occur in the transition between regular and Mach reflection as had been predicted, and his related numerical and experimental contributions. I also showed his resolution of the "von Neumann Paradox" by DSMC and Navier-Stokes computations. In the second part I showed experimental results in which a regular reflection in the dual-solution domain was tripped to Mach reflection by laser energy deposition showing that Mach reflection is more stable than regular reflection in that domain.

The second Ivanov session started with a presentation by Ketsdever on A spacecraft's own ambient environment. I missed this talk because I attended Luding's invited talk.

The next presentation in the Ivanov session was by Yoshida and Aoki on "A DSMC study of the Taylor–Couette problem for a vapor–gas mixture". Aoki was the presenter. DSMC simulation is used in the near–continuum regime. This is an interesting variant of Taylor–Couette flow in which the vapor is evaporated wall material. The evaporation and condensation on the cylinder walls causes a weak radial flow that stabilizes the flow. In this situation three flow configurations are shown to exist stably.

Bruno presented "DSMC simulation of thermal fluctuations". Optical experimental observations of density fluctuations in gases are compared with simulations using DSMC with good agreement.

The last presentation in the Ivanov sessions was by Alina Alexeenko, a former student of Mikhail Ivanov. Her title was "Rarefied microflows: modeling by DSMC and beyond". She showed how Ivanov pioneered microflows as an application of RGD and reviewed new micro and nano technologies in which RGD is relevant. An example was a "shock tube in a pocket".

In parallel to the Ivanov session there was a presentation by Ling, Cai and He on "An introduction on the novel plume effects experimental system", which I did not attend, but which is worth commenting on. This is a large (5 m diameter, 12 m long) new facility at Beijing University, which has the capability of maintaining space–like vacuum conditions while testing thrusters. As far as I know this is only the second such facility in the world, the first being the STG built 1990 in Göttingen, Germany.

O'Neill, Strongrich, Cofer and Alexeenko were the authors of "Measurements and simulations of Knudsen thermal force". Alexeenko was the presenter. The Knudsen thermal force also called the radiometric force arises in the presence of temperature gradients in a rarefied gas. It peaks around a Knudsen number of 1. Experiments in which a heated and cold plate are placed in close proximity were made with a micro–Newton balance to measure the Knudsen force. Geometrical parameters and pressure were varied. This permitted variation of the Knudsen number from 0.01 to 10. Significant increase of the force over results with uniform heating were observed. Simulations show two circulation regions are established by the differential heating. The forces measured are in the order of tens of micro–Newtons.

Li and two co–authors presented "Knudson torque on heated micro–beams". By shaping small heated objects in a gas at Knudsen number greater than 0.01 it is shown that it is possible to generate Knudsen torque that can be used to manipulate tiny parts. Pendulum motions and rotations were demonstrated. Rotational speeds up to 3 rpm could be reached. Since the angular speed is proportional to the square of the Knudsen number, rarefaction

greatly increases it. This appears to have numerous applications in micro fabrication and manipulation.

Kudryavtsev and two co-authors presented "Aerodynamic focusing of particles in supersonic micronozzles at small Reynolds numbers". Nozzles with exit diameter  $127\text{ }\mu\text{m}$  and flow speeds around 100 m/s are used in many industrial applications to focus particles that are carried with the flow. Their interest is whether this also happens if the flow is supersonic. The flow of the carrier gas is simulated by Navier–Stokes, and the particle motion is treated with Lagrangian method. The drag on the particles is calculated using a bridging function. It turns out that good focusing is obtained in two separate regions of the size spectrum:  $2 - 3\text{ }\mu\text{m}$  and 200 - 300 nm. The focusing point depends on the particle size.

Yonemura and six co-authors presented "A study of floating of a slider with micro/nano scale structure on a rotating disk". The friction between two surfaces in a gas is greatly reduced as relative speed increases. They studied this using DSMC when one of the surfaces has triangular dimples. It turns out that the pressure distribution on the dimpled surface is asymmetric, giving rise to a forward force. The force is increased when the gap is reduced and when the speed is increased. Good agreement is found with lubrication theory.

Kawagoe and five co-authors from the same group presented "Numerical analysis of micro-/nanoscale gas–film lubrication of sliding surface with complicated structure". As in the previous talk, DSMC is used to study the case when the structure of one of the surfaces is more complicated than regular triangular dimples, at a Knudsen number above 0.1. They measured a real surface by atomic force microscopy and reproduced it using a marching cubes method. The minimum clearance was  $0.28\text{ }\mu\text{m}$ . The computed pressure distribution produces a lift force that increases with decreasing spacing and increasing speed.

Ramanan and two co-authors presented "Experimental and numerical characterization of a micro–resonator for low pressure sensing". At low gas pressure the damping of a micro–resonator is highly dependent on the pressure. They excite the resonator electrically and sense the amplitude of vibration capacitively. It was found that the fractional change in quality factor of the oscillation is approximately equal to the fractional change in pressure. Measured and computed (with DSMC) values of the quality factor agreed to within 20%.

Oskar and Manela presented "The response of a confined rarefied gas to non–periodic acoustic excitation". They linearize the BGK model equation, transform to Fourier space, solve for each frequency and transform back to time. They find that waves propagate at the mean thermal speed and decay faster at larger  $K$ . They cover the whole range of  $K$  and compare with continuum and collisionless limits.



Pogorelyuk and Manela from the same group presented "Approach to acoustic cloaking in rarefied gases". In acoustic excitation from a wall, they replaced the usual isothermal wall condition with different specifications of the heat flux. They applied DSMC and found that it is possible to optimize the heat flux profile to achieve acoustic cloaking.

Croizet and Gagniol presented "Asymptotic modeling of the axisymmetric flow of a binary gas mixture in a circular microchannel". With small radius to length ratio they derived a set of ordinary differential equations using slip boundary conditions at moderate  $K$  and small Reynolds number. These were solved using MATLAB. They compared results with DSMC in some cases. The method permits wide variation of parameters since the calculations are cheap.

These were all the presentations that I attended. I want to remind readers that the fields covered in the Symposium were often outside my expertise, and I worked from hand-written notes taken during the presentations, so that I ask for leniency in places where I might have made mistakes. I did go to the poster sessions, but I was always distracted into discussions with participants and did not really spend enough time to be able to comment on any of the posters intelligently. This is unfortunate, because the large number of student participants were concentrated into these two sessions and a better look might have provided a glimpse into the future of the RGD Symposia.

## **5 General Remarks**

A striking feature was the ubiquity of DSMC. In my report the acronym occurs more than thirty times. It has become such an important tool in RGD that researchers either use it as a tool or work on methods to improve it. Hybrid methods that use continuum CFD in dense parts of a flow field and switch to DSMC in more rarefied regions also abound. Among these, Gorji's DSMC/Fokker-Planck hybrid method is particularly elegant. Gallis even advocates DSMC for continuum flows, but then, not everyone has available the computing power of Sandia Labs.

As in other fields the fraction of presentations with experimental components has decreased over the last two decades. This is true although, as is the case in this Symposium, sophisticated new methods are being developed. I was sorry to see that researchers from NASA could not obtain authorization for travel to China.

My observation in this and other conferences has been that the development of new facilities in China and the quality of the research work and presentations coming from Chinese

laboratories is continuing to advance rapidly. It was particularly pleasing to see the large number of student attendees, particularly from China, see Appendix.

The general quality of the presentations was high. There were a few that seemed to me to make only incremental contributions, but quite a number that had exciting new developments.

The Advisory Committee decided that the next (30th) RGD Symposium will be organized by Henning Struchtrup at Victoria University in Canada in 2016.

## 6 Appendix: Participant Statistics

Country	Participants	Students	Acc. Pers.
China	44	40	1
Russian F.	26	4	4
Japan	15	4	1
US	14	3	4
France	9	1	3
Germany	7	5	2
Italy	7	0	1
S. Korea	4	5	0
India	4	2	0
Turkey	3	0	0
Israel	2	0	0
Australia	2	0	1
Kazakhstan	2	0	1
Switzerld.	1	2	1
Canada	1	3	0
UK	1	1	1
Greece	1	0	0
Iran	1	0	0
Netherlands	1	0	0
Spain	1	0	0
Brazil	0	1	0
Totals	146	71	20